Step-Down Switching Regulator

for Negative Voltages

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Special switching regulator ICs for negative voltages are conspicuously absent in the catalogues of semiconductor manufacturers. However, you can make do with a positive-voltage regulator IC and a few circuit tricks.

Switching regulator ICs are used for voltage conversion with minimal losses. If you want build a high-efficiency circuit to convert a positive voltage to a higher or lower voltage, you can choose from a large number of switching regulator ICs from several manufacturers. However, if you want to convert a negative voltage, the situation is rather different. There are practically no special ICs available for this purpose, and typical application circuits showing how this problem can be solved are equally scarce.

This article shows how a step-down regulator for negative voltages can be built using readily available positive-voltage switching regulator ICs.

Basic circuits

There are many different types of switching regulator ICs that can be used to convert positive voltages into other positive voltages, and they employ several different working principles. Some ICs use chokes for energy storage, while others use capacitors, but the latter type is of no interest for our purposes.

Switching regulator ICs that use storage chokes can be divided into step-down and step-up types. In **Figure 1,** the operating principle of each type is shown at the top and the usual complete circuit is shown at the bottom. Depending on the type of IC used, additional components may be needed for compensation, and various shutdown or sync inputs may also be present.

A step-down regulator converts a voltage into a lower voltage by applying a switched voltage to the storage choke. The combination of the choke and the following storage capacitor acts as a low-pass filter, which removes the switching frequency from the output voltage. The voltage divider at the feedback (FB) pin determines the value of the output voltage, since the IC will adjust the switching rate or duty cycle such that the voltage at the FB pin matches the internal reference voltage (usually +1.25 V or +1.5 V).

The second basic circuit is the step-up regulator (**Figure 1b**), which generates an output voltage that is higher than the input voltage. In such a regulator, one terminal of the choke is connected directly to the input voltage, while the other terminal is temporarily connected to ground by the switch in the IC. This causes the choke to build up stored energy in the form of a magnetic field in its ferrite core. When the switch is opened, a voltage with the opposite polarity is induced by the collapsing magnetic field and appears at the terminals of the choke. This voltage adds to the input voltage to produce a higher voltage, which is passed to the output capacitor via the diode. The diode also prevents the output capacitor from discharging through the switch. The physical effect can be understood as follows: when the switch is opened, the current in the choke wants to continue flowing. The only way it can do so is to flow through the diode into the capacitor and the load.

A step-up regulator also has a voltage divider connected to the feedback (FB) sense input. The IC regulates the duty cycle or pulse rate such that the output voltage has the desired value.

Using a step-up switching regulator as a step-down regulator for negative voltages

Although there aren't any ICs for negative-voltage step-down switching regulators, we can make do with ICs that are actually intended to be used for positive voltages. If you look at the basic circuit for a negative-voltage step-down switching regulator in **Figure 2**, which is a modified version of the circuit shown in Figure 1a, you can clearly see that a positive-voltage step-up regulator IC can be used to chop the negative input voltage and then smooth the

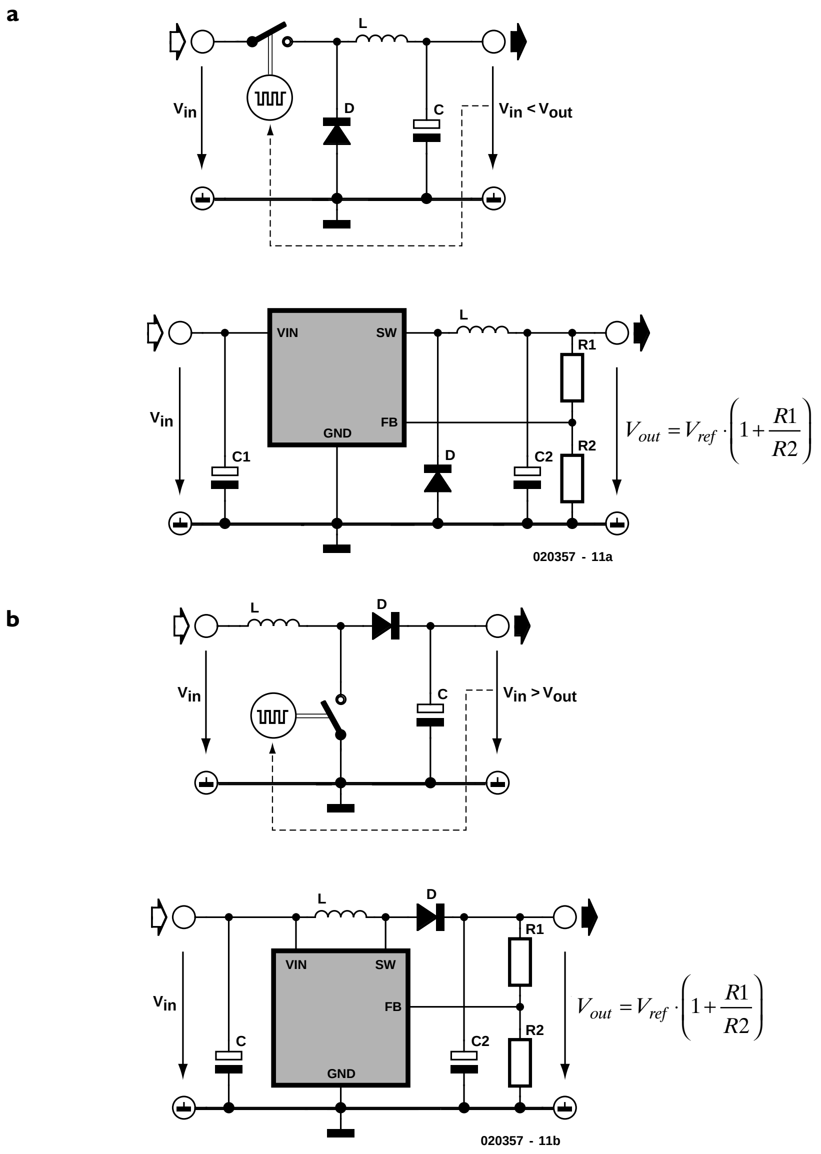


Figure 1. Switching regulators:
a) step-down, b) step-up

result using the LC low-pass filter, yielding an output voltage having a smaller magnitude and a negative sign.

Of course, here you must bear in mind that the positive supply voltage pin of the IC has to be connected to ground, while the GND pin of the IC has to be connected to the negative input voltage. All external components, such as compensation capacitors, must be connected to the negative input voltage instead of ground.

Generating the feedback signal

The only problem with this circuit is the direction of regulation of the feedback signal and its reference potential. The lower end of the feedback voltage divider is normally connected to the GND pin of the IC, which is now connected to the potentially variable input voltage. It is thus obvious that this simple voltage divider cannot be used as is. Instead, we must generate a voltage between the FB and GND pins of the IC that is directly dependent on the negative output voltage but referenced to the negative input voltage. Several potential solutions are shown in **Figure 3**.

Figure 3a shows a circuit using an operational amplifier with its non-inverting input connected to a potential partway between V_{out} and V_{FB}, which is labelled 'V_{shift}'. Resistors R1 and R2 at the inverting input of the opamp have equal values, so the voltage at the FB pin of the switching regulator IC is lower than V_{shift} by exactly the amount that V_{out} is higher than V_{shift}. The two voltage differences can be visualised as two level arms whose common pivot point is V_{shift}. These arms have equal lengths because the resistors have equal values. The formulas for calculating the value of V_{shift} are shown in the figure.

The drawback of this circuit is that the output voltage also depends on the level of the input voltage (via V_{shift}). If the input voltage varies, the output voltage will vary accordingly. One way to improve this circuit in this regard would be to use a Zener diode to stabilise the voltage divider (R3 and R4) However, the resulting circuit would be quite a bit more complicated than the other alternatives, which we can now examine.

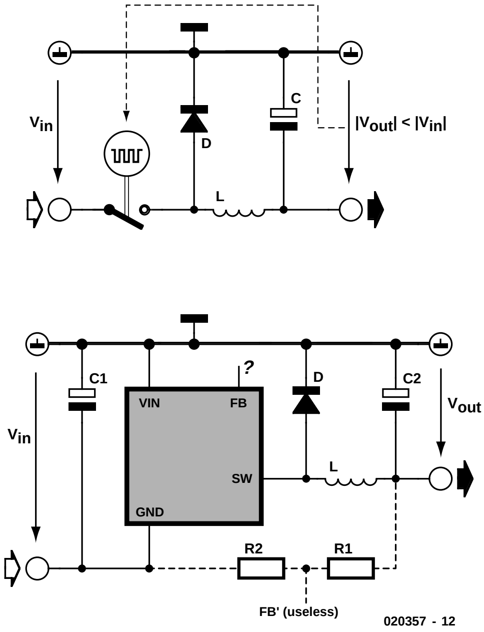
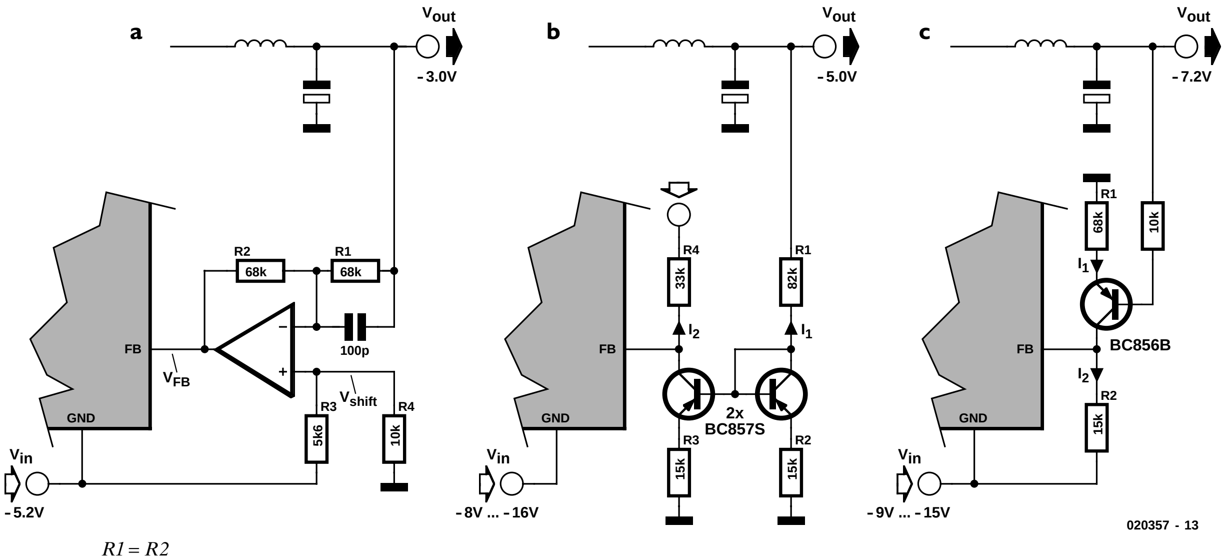


Figure 2. Basic circuit for a negative step-down switching regulator



$$R1 = R2$$

$$V_{Shift} = V_{in} \cdot \frac{R4}{R3+R4}$$

$$= \frac{V_{out} - V_{FB}}{2}$$

$$V_{FB} = V_{in} + V_{Ref}$$

$$\Rightarrow V_{out} = \frac{R4-R3}{R4+R3} \cdot V_{in} - V_{Ref}$$

$$\left|V_{out}\right| = \frac{R1+R2}{R4} \cdot V_{Ref} + V_{BE}$$

$$R4 = \frac{V_{Ref}}{\left|V_{out}\right| - V_{BE}} \cdot \left(R1+R2\right)$$

$$V_{BE} = 0.6V$$

$$\left|V_{out}\right| = \frac{R1}{R2} \cdot V_{Ref} + V_{BE}$$

$$R1 = \frac{\left|V_{out}\right| - V_{BE}}{V_{Ref}} \cdot R2$$

$$V_{BE} = 0.6V$$

Figure 3. Various options for generating the feedback signal: a) using an opamp as an inverter, b) using a current mirror, c) using a transistor

As shown in **Figure 3b**, the feedback voltage can also be reversed using a current mirror. Here a current flows through resistors R1 and R2 and the right-hand transistor, which is wired as a diode. As indicated in the figure, this current is determined by the value of the output voltage (less a diode voltage drop of approximately 0.6 V) and the values of the resistors. Since R2 and R3 have equal values, a current of the same magnitude must flow through R3, particularly as the base-emitter junction of the left-hand transistor is wired exactly the same as that of the right-hand transistor. The collector current of the left-hand transistor is thus equal to the current in R3, assuming that the base current can be neglected. This current flows into the negative supply line via R4, producing a feedback voltage with the proper polarity for the feedback (FB) pin of the switching regulator IC. This circuit is fully independent of the value of the input voltage, since the two equal currents in the current mirror depend only on the value of the output voltage.

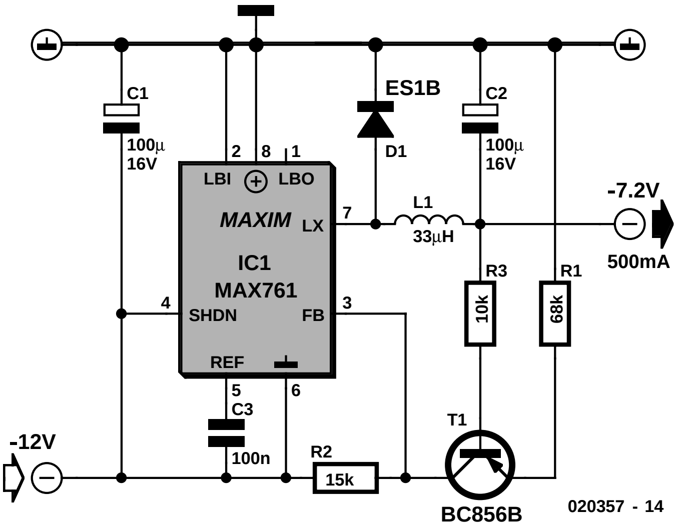


Figure 4. Negative-voltage step-down switching regulator using a MAX761

The simplest circuit for generating the FB signal requires little more than an ordinary PNP transistor, as shown in **Figure 3c**. The base of the transistor is connected to the negative output voltage by a series resistor, whose exact value is not critical. The negative output voltage, reduced by the forward voltage of the base-emitter junction (approximately 0.6V), also appears at the upper end of the emitter resistor. The resulting current also flows from the collector of the transistor through R2 to the negative input voltage. If the transistor has sufficiently high current gain (β > 100), the base current

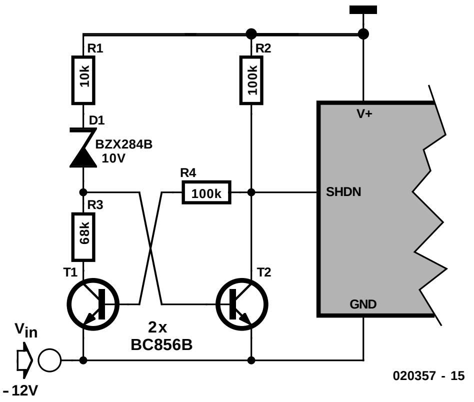


Figure 5. Auxiliary shutdown circuit

can safely be neglected. The voltage drop thus generated across R2, which depends on the value of the output voltage, provides the necessary input for the FB pin of the switching regulator IC. It can also be seen that the output voltage appears across R1 and the base-emitter junction of the transistor, while V_{FB} (the reference voltage the switching regulator IC, usually 1.25 V or 1.5 V) appears across R2. Consequently, the magnitude of the input voltage must be greater than the magnitude of the output voltage by at least V_{FB}.

–7.2 V at 0.5 A from –12 V

Now it's time to try out our theory with an actual circuit, which is shown in **Figure 4**. Here we use a Maxim MAX761 step-up switching regulator IC, which can supply a current of up to 0.5 A in this type of circuit. Diode D2 is an ultrafast Schottky diode (General Semiconductor type ES1B). If somewhat higher losses are acceptable, other types of Schottky diodes can also be used. A 33-µH SMD coil from the TDK SFL series (type SLF12575T-330M3R2) has been selected for the storage choke. The electrolytic capacitors must have low effective series resistance (ESR). Suitable types are available from several manufacturers. The lower their ESR, the better the capacitors can filter out the residual components of the switching frequency.

The circuit shown in Figure 4 can be constructed in a very compact form. Its efficiency, which is ratio of the output power (2.88 W in this case) to the input power (3.36 W), is approximately 86 percent at an output current of 400 mA. The output voltage is determined by the values of resistors R1 and R2, which can be calculated using the formulas given in Figure 3c.

Delayed switch-on

As we have seen in Figure 3c, the feedback mechanism using a transistor as a voltage converter only works properly above a certain magnitude of input voltage, to wit the magnitude of the output voltage plus V_{FB} (which is usually 1.25 V or 1.5 V). Consequently, we can add a small circuit connected to the shutdown pin of the switching regulator IC to disable it until the input voltage has reached the required level (see **Figure 5**).

This circuit works as follows: if the magnitude of the input voltage increases from 0 V towards –12 V, at first T1 conducts, since it receives base current via the two 100-Ω resistors R2 and R4. It thus holds the base of transistor T2 at ground potential, cutting it off. This situation only changes when Zener diode Z1 starts to conduct, which occurs when the input voltage is sufficiently great (–11 V in this case). When Z1 conducts, T2 switches on, which causes the circuit to toggle due to the feedback provided by resistor R4. As the collector–emitter current of T1 drops, the base current of T2 increases, further driving T1 towards cut-off.

The Zener voltage of diode Z1 roughly determines the voltage at which the SHDN input is released. It must be chosen according to the input voltage range. Also, this circuit only works with step-up regulator ICs that are enabled when the SHDN input is at ground potential. For many types of switching regulator ICs, this input is labelled '$\overline{\text{ON}}$', but its function is the same.

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